Original Article
J. Korean Wood Sci. Technol. 2025, 53(5): 536-549
https://doi.org/10.5658/WOOD.2025.53.5.536

Journal of the Korean Wood Science and Technology
pISSN: 1017-0715 eISSN: 2233-7180
http://www.woodj.org

Characteristics of Wood Plastic Composites from Four Blend Ratios of Alkali-Treated Ulin (*Eusideroxylon zwageri*) and Sengon (*Falcataria moluccana*) Wood Flour

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ABSTRACT

In this study, we investigated the effects of wood flour composition (ulin and sengon) and 5% NaOH alkali treatment on the physical and mechanical properties of wood-plastic composites bonded with unsaturated polyester resin. Four formulations were developed using different blend ratios of ulin and sengon, with alkali treatment applied only to ulin-wood flour. The physical tests evaluated density, moisture content, water absorption, and swelling thickness. The mechanical evaluations included the modulus of elasticity (MOE), modulus of rupture (MOR), tensile strength, impact strength, and internal bond strength (IBS). Analysis of variance results (α = 0.05) showed that treatment variations significantly affected all physical properties except density, and significantly influenced mechanical properties such as MOE, MOR, tensile strength, and IBS. No significant differences were observed in impact strength. The best mechanical performance was achieved by P4, which recorded the highest MOE (1,001.4 N/mm^2), MOR (12.04 N/mm^2), tensile strength (8.12 N/mm^2), and impact strength (0.0084 J/mm^2). P1 exhibited the highest IBS value (1.52 MPa). Although none of the treatments met the structural strength thresholds of SNI 8514:2015, the composites exhibited adequate dimensional stability and mechanical consistency. When benchmarked against the ASTM D7031 and JIS A 5908 performance guidelines, these results support their potential use in nonstructural applications, such as indoor cladding, ceiling panels, partition walls, and furniture components, especially in applications where dimensional stability and moisture resistance are more critical than high mechanical strength.

Keywords: alkali pretreatment, non-structural application, polyester resin, sengon, ulin, wood plastic composite

1. INTRODUCTION

Over the past two decades, wood-plastic composites (WPC) have gained considerable attention as environmentally friendly materials that combine the mechanical strength of wood with the durability of synthetic polymers (Gurunathan *et al.,* 2015; Zyryanov *et al.,* 2024). WPCs are widely used across various sectors, ranging from the construction industry to the automotive industry. The growing global awareness regarding the importance of sustainable development and circular economy has further accelerated research and development of WPCs, particularly for those utilizing agricultural or industrial waste as a reinforcement filler (Deka and Maji, 2011; Setiawan *et al.,* 2023). Wulan *et al.* (2025) suggested that issues in the furniture industry, such as

Date Received May 14, 2025; Date Revised July 24, 2025; Date Accepted August 12, 2025; Published September 25, 2025
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raw material shortages, can be addressed by utilizing wood waste as a marketable product, a step that also positively impacts the environment. From a market perspective, the global demand for WPC has significantly increased. The WPC market is projected to grow from USD 7.5 billion in 2023 to USD 11.9 billion by 2028, with a compound annual growth rate of 9.8%, driven by the increasing demand for sustainable construction materials and advancements in plastic recycling technologies (Marketsandmarkets, 2024).

WPCs support the global efforts to reduce the exploitation of natural resources. These composites are typically produced from wood fibers or wood flour combined with recycled thermoplastic polymers, which not only helps reduce waste but also contributes to circular economy (Widiastuti *et al*., 2025). WPCs offer an alternative to decrease the dependence on conventional materials such as solid wood and virgin plastics, which negatively impact the environment (Khan *et al.,* 2021). WPC development has been supported by extensive research in Indonesia and globally. Most previous studies have focused on using wood flour from a single species and combining it with different polymer matrices.

Numerous wood flour–polymer combinations have been investigated, such as sengon wood flour with polyester (Rahman *et al.,* 2018), larix board with PU, PVAc, PRF, MF and UF adhesive (Lee and Oh, 2022), camphor wood with LDPE (Nurwendi *et al.,* 2016), teak sawdust and UF (Wanishdilokratn and Wanishdilokratn, 2024), mahogany wood with polyester resin (Gapsari and Setyarini, 2010) or polypropylene (PP; Vedat, 2020), as well as other combinations like lamtoro-PP (Lestary *et al.,* 2022), pine-PP (Gurau and Ayrilmis, 2018) rubberwood with silica filler (Chotikhun *et al.,* 2024). In addition to wood flour, coconut coir fibers have been combined with PVC (Rimdusit *et al.,* 2011). Nevertheless, there remains significant room for exploration, particularly in the development of WPC that incorporate two wood species with contrasting physical and mechanical properties. One promising yet underexplored combination includes ulin wood (*Eusideroxylon zwageri*), a tropical hardwood known for its high density (D) and exceptional durability, and sengon wood (*Falcataria moluccana*), which is a lightweight and fast-growing species.

In the present study, ulin and sengon wood flour were selected based on geographical and local resource considerations. This study was conducted in East Kalimantan, a region that is the natural habitat of the ulin and a center for community forest plantations, where sengon is widely cultivated as a fast-growing and economically valuable commodity. Ulin, which is locally valued for its natural resistance to decay and high mechanical strength, is often underutilized in its waste form (Sari *et al.,* 2023). Sengon, on the other hand, is a widely cultivated, fast-growing species that provides lightweight but relatively weaker wood particles (Dirna and Wahyuningtyas, 2025; Laksono *et al.,* 2023; Rahayu *et al.,* 2021). The combination of these two species as filler materials in WPC offers a unique opportunity to develop hybrid composites that balance the strength, D, and economic viability. The utilization of these residues promotes waste reduction and supports sustainable material practices.

In this study, ulin wood flour was chemically treated using a 5% NaOH alkaline solution prior to mixing with the polymer matrix. Alkali treatment aims to enhance the interfacial bonding between the wood fibers and the polymer by removing amorphous components such as lignin, hemicellulose, oils, and surface impurities (Wu *et al.,* 2023). According to Nawawi *et al.* (2023), the NaOH solution degrades hemicellulose; hence, the amorphous fractions that play a role in water absorption (WA) and molecular binding diminish. Given that ulin is known for its high D and natural oiliness, the treatment is expected to open the pores of the wood particles, thereby improving interfacial adhesion with the unsaturated polyester resin and facilitating better load transfer within the composite structure. Although alkali treatment has been widely applied to low-D wood species, its effect on dense tropical hardwoods such as ulin remains under-explored, making it a novel aspect of the present study.

Unsaturated polyester resin was selected as the matrix material because of its advantageous properties, including excellent moldability, good mechanical strength, and resistance to weathering and chemical exposure (Davallo *et al.,* 2010). Compared to thermoplastic polymers such as PP or polyethylene, polyester resin exhibits better adhesion to wood surfaces, facilitating stronger interfacial bonding between the wood and matrix phases (Keya *et al.,* 2019). Additionally, polyester offers practical, such as a relatively fast curing time, harder final product, and superior thermal deformation resistance, making it a suitable choice for lightweight structural applications of WPC.

In this study, we aimed to investigate the effect of combining 5% NaOH-treated Ulin wood flour with Sengon on the physical and mechanical properties of WPCs. The study considered the local availability of raw materials, the applied chemical treatment, and the suitability of the chosen polymer matrix. The selected materials can yield a composite with an optimal balance of strength, D, and economic feasibility while also supporting the sustainable utilization of local resources. The primary objective of this study was to analyze the effects of wood flour composition (ulin and sengon) and 5% NaOH alkali treatment on the physical and mechanical properties of WPC bonded with unsaturated polyester resin.

2. MATERIALS and METHODS

2.1. Preparation of raw materials

Ulin (*E. zwageri*) and sengon (*F. moluccana*) wood flour were obtained from Samarinda City and Jonggon Village, East Kalimantan, Indonesia, respectively. The wood flour was sieved through 16- and 30-mesh screens, and the fraction retained between the 16- and 30-mesh was used for WPC fabrication. Sengon flour was sun-dried to a moisture content (MC) of approximately 12%, whereas ulin flour was subjected to 5% NaOH treatment prior to drying.

2.2. Alkali pretreatment of ulin wood flour

A 5% (w/v) NaOH solution was prepared by dissolving 50 g of NaOH in 1,000 mL of deionized water. Ulin wood flour was fully immersed in the solution and stirred intermittently for 2 h to ensure uniform alkali penetration. The flour was then rinsed with deionized water until the rinsate reached a neutral pH (confirmed using litmus paper) and subsequently sun-dried until its MC dropped below 12%.

2.3. Polymer preparation

An unsaturated polyester resin and its corresponding hardener were used in this study. The resin was mixed with the hardener in a ratio of 100:2 (g/g) and stirred until homogeneous. The mixture was then combined with the wood flour and stirred thoroughly to ensure uniform dispersion.

2.4. Wood-plastic composites manufacturing process

Wood flour (ulin and sengon) was first mixed at the stated ratio until homogeneous. The resin and catalyst were then mixed and stirred, followed by the addition of the resin to the wood flour mixture. The composite mixture was placed in a mold lined with aluminum foil and pressed at 4,000 kN/m^2 (40 bar) at 100℃ for 15 min. After pressing, the panels were reinforced with metal plates, clamped for 24 h, and conditioned at room temperature (25℃) for 14 days. Final conditioning was performed at 20℃ and 65% relative humidity to stabilize the composite before testing. Table 1 lists the composi-

Table 1. Composition and alkali treatment of WPC samples

Sample code	Wood flour composition		Alkali pretreatment
	% Ulin	% Sengon	
P1	75	25	Yes (Ulin)
P2	50	50	Yes (Ulin)
P3	25	75	Yes (Ulin)
P4	50	50	No

WPC: wood-plastic composites.

tions and alkali treatments of the WPC sample.

Treatment codes were assigned based on the wood flour ratio and type of treatment. Notably, only the ulin flour was alkali-treated in treatments P1, P2, and P3, while treatment P4 used untreated ulin.

2.5. Testing of physical and mechanical properties

The WPC was evaluated according to the ASTM Standards. The physical properties tested included D, MC, WA, and thickness swelling (TS). The mechanical properties included the modulus of elasticity (MOE), modulus of rupture (MOR), internal bond strength (IBS), tensile strength (σt), and impact strength (IS). All the physical and mechanical tests were conducted on 10 samples per treatment group.

2.5.1. Density and moisture content

Specimens (50 mm × 50 mm × 6 mm) were tested using ASTM D2395 and ASTM D4442. The samples were oven-dried at 103 ± 2℃ for 24 h.

$$D\ (g/cm^3) = (M / V) \quad (1)$$

$$MC\ (\%) = (A - B) / B \times 100 \quad (2)$$

Where M is the oven-dried mass, V is the volume (cm^3), A is the initial mass (g), and B is the oven-dried mass (g).

2.5.2. Water absorption and thickness swelling

Specimens (50 mm × 50 mm × 6 mm) were tested according to ASTM D1037. The samples were then submerged in water for 24 h at room temperature.

$$WA\ (\%) = [(m_2 - m_1) / m_1] \times 100 \quad (3)$$

$$TS\ (\%) = [(T_2 - T_1) / T_1] \times 100 \quad (4)$$

Where m_1 and m_2 are the masses before and after immersion (g), respectively; T_1 and T_2 are the thicknesses before and after immersion (mm), respectively.

2.5.3. Modulus of elasticity and modulus of rupture

Flexural tests were conducted using 200 mm × 50 mm × 6 mm specimens with a span of 150 mm using a universal testing machine (UTM), in accordance with ASTM D1037.

$$MOE\ (N/mm^2) = (3 \times P_{max} \times L) / (2 \times b \times d^2) \quad (5)$$

$$MOR\ (N/mm^2) = (P \times L^3) / (4 \times D \times b \times d^2) \quad (6)$$

Where P_{max} is the maximum load (N); P is the applied load (N); L is the span length (mm); b is the width (mm); d is the thickness (mm); and D is the deflection at the proportional limit (mm).

2.5.4. Internal bond strength

Evaluated on specimens (50 × 50 × 6 mm) using UTM per ASTM D1037.

$$IBS\ (MPa) = P_{max} / (a \times b) \quad (7)$$

Where P_{max} is the maximum load (kg), and a and b are the sample width and length (mm), respectively.

2.5.5. Tensile strength

Based on ASTM D3039 using UTM.

$$\sigma t \text{ (MPa)} = P_{max} / (a \times c) \quad (8)$$

Where P_{max} is the maximum load (kg), a is width, and c is thickness (mm).

2.5.6. Impact strength

Notched Izod test was conducted using specimens (length 124.5–127.0 mm, width 20 mm, thickness 7.08–8.86 mm), following ASTM D6110.

$$IS = E / A \quad (9)$$

Where E is the energy absorbed (Joule), and A is the cross-sectional area (mm^2).

2.6. Data analysis

Data were analyzed using one-way analysis of variance (ANOVA) to determine significant differences between treatments for each parameter (D, MC, WA, TS, MOE, MOR, IBS, and tensile and ISs), followed by least significant difference (LSD) post hoc test. All calculations were performed using Microsoft Excel.

3. RESULTS and DISCUSSION

3.1. Physical properties of wood-plastic composites

Table 2 presents the physical properties (D, MC, WA, and thickness) of the WPCs developed in this study across the four treatments. Statistical analysis using ANOVA followed by LSD post hoc test revealed significant differences ($p < 0.05$) in all properties except D, indicating that the treatment variation influenced the physical behavior of the WPC.

The D of the WPC samples ranged from 0.49 to 0.56 g/cm^3. According to SNI 8514:2015, the minimum required D for a WPC is ≥ 0.609 g/cm^3. Therefore, the results obtained in this study were slightly lower than the national standards. This discrepancy can be attributed to several factors. First, sengon wood flour has a lower intrinsic D than ulin; therefore, increasing the proportion of sengon tends to reduce the overall D of the composite. Second, the wood flour to-polyester resin ratio, along with the effect of the 5% NaOH alkali treatment, influenced the internal structure and compaction behavior of the composite during molding.

Although polyester resins have a relatively high specific gravity, their rigid and brittle nature may lead

Table 2. Physical properties of WPC samples under different treatments

Treatments	Density (g/cm^3)	Moisture content (%)	Water absorption (%)	Thickness swelling (%)
P1	0.52 ± 0.04	3.50^a ± 0.44	6.1^a ± 1.22	3.22^a ± 0.50
P2	0.51 ± 0.02	5.53^b ± 0.60	4.6^b ± 1.06	4.04^b ± 0.43
P3	0.49 ± 0.05	7.96^c ± 0.94	4.1^c ± 1.04	4.15^c ± 0.53
P4	0.56 ± 0.07	3.25^a ± 0.35	6.6^d ± 0.71	1.71^d ± 0.52

$^{a-d}$ Values in the same column followed by different letters indicate significant differences ($p < 0.05$) based on the LSD post hoc test.
WPC: wood-plastic composites, LSD: least significant difference.

to void formation owing to the limited penetration and non-uniform coating of wood particles (Spigarelli and Paoletti, 2018). These voids disrupt matrix continuity and reduce the final composite D. Despite these variations, the ANOVA results indicated no statistically significant differences in D among treatments ($p > 0.05$). However, only minor numerical variations were observed.

The MC ranged from 3.25% to 7.96%, with P4 showing the lowest MC, and P2 the highest. Statistical analysis using ANOVA followed by LSD post hoc test revealed that these differences were significant at $\alpha = 0.05$, indicating that the variation in wood flour composition and treatment had a meaningful impact on the MC of the composites. According to SNI 8514:2015, the recommended MC for WPC products is below 5%. Based on this criterion, only treatments P1 and P4 met the standards, whereas treatments P2 and P3 exceeded them.

The elevated MCs in treatments P2 and P3 may be due to the more porous cell structure of sengon flour (Rahayu *et al.,* 2021). Alkali (NaOH) pretreatment increases the number of exposed hydroxyl groups by removing hemicellulose and surface extractives, thereby enhancing the hydrophilicity of the fiber surface (Rowell, 2012). Although polyester is hydrophobic, its limited penetration can result in interfacial gaps, especially after fiber swelling caused by the alkali treatment, which allows moisture to infiltrate.

The WA values of the WPC panels differed significantly among treatments, ranging from 4.1% (P3) to 6.6% (P4). ANOVA revealed that the variations in the composition of ulin and sengon wood flour significantly affected (α = 5%) WA capability of the composites. This indicated that the differences in water uptake were influenced by the type of wood used and the chemical treatment applied.

The lowest WA was recorded in treatment P3, indicating that a higher proportion of sengon, which is known for its lower D and more porous structure, allowed for better matrix penetration and more efficient interfacial bonding, thereby reducing the voids and pathways for moisture ingress. This finding is consistent with that of Cheah *et al.* (2017), who reported that a more homogeneous filler distribution and denser internal structure reduced WA.

In contrast, the highest WA was observed for treatment P4, which was likely due to the absence of alkali pretreatment. Without this treatment, wood particles tend to retain extractives that are hydrophilic in nature and have rougher surfaces, which hinder effective bonding with the polyester matrix and result in more capillary space for water to enter (Chang *et al.,* 2014). Although alkali pretreatment improves water resistance by removing surface impurities (Khalil *et al.,* 2012; Zhou *et al.,* 2009), its absence in P4 can likely increase moisture uptake.

The TS values of the WPC samples varied significantly across treatments (α = 5%), with the highest value observed in P3 (4.15%) and the lowest in P4 (1.71%). According to SNI 8514:2015, the maximum allowable swelling thickness after 24-hour water immersion was 12%, indicating that all treatments in this study met the standard and were considered suitable for use.

TS ranged from 1.71% (P4) to 4.15% (P3), and showed statistically significant differences among the treatments. All samples met the maximum allowable swelling thickness of 12% after 24 h of water immersion, as stipulated in SNI 8514:2015. The high swelling observed in P3 correlated with its low D and high MC, which allowed water to penetrate deeper into the cell walls and cause expansion. Conversely, despite its high WA, P4 exhibited the lowest swelling, possibly because of its less compact internal structure, which absorbs water into the voids without causing cell wall expansion. Treatments P1 and P2 exhibited intermediate swelling, with a general trend indicating that higher ulin content reduces swelling, likely because of its high lignin and oil content, which contributes to its hydrophobic nature.

Although the treatments did not satisfy the minimum D requirements specified by SNI 8514:2015, the WPC samples exhibited acceptable physical properties, particularly in terms of moisture resistance and dimensional stability. When evaluated against performance expectations outlined in ASTM D7031 and JIS A 5908, these physical characteristics indicate that the materials are suitable for non-structural applications such as indoor wall cladding, ceiling panels, partition boards, and furniture back panels. Accordingly, these composites show potential for use as lightweight construction elements, where moisture durability and shape stability are prioritized over mechanical strength.

3.2. Mechanical properties of wood-plastic composites

The mechanical properties of the WPC used in this study include the MOE, MOR, st, IS, and IBS (Table 3). Statistical analysis using ANOVA and LSD post hoc tests showed that the MOE, MOR, st, and IBS differed significantly among treatments ($p < 0.05$), indicating a substantial effect of ulin–sengon wood flour composition and alkali treatment on the mechanical performance of WPC. However, the differences in IS were not statistically significant ($p > 0.05$), suggesting a relatively uniform response across the treatments for this parameter.

Among the different treatments, MOE values ranged from 650.3 N/mm^2 (P3) to 1,001.4 N/mm^2 (P4), while MOR ranged from 6.13 N/mm^2 (P3) to 12.04 N/mm^2 (P4). All values were below the minimum requirements specified in SNI 8514:2015: 2,950 N/mm^2 for the MOE and 25 N/mm^2 for the MOR. However, ASTM D7031-11 does not prescribe fixed thresholds but rather provides performance benchmarking guidelines, suggesting that these values may still be acceptable for light-duty, non-load bearing uses.

Treatment P4 exhibited the highest MOE and MOR values (1,001.4 N/mm^2 and 12.04 N/mm^2, respectively). The absence of chemical treatment (NaOH) likely preserved the natural lignocellulosic structure of the wood, which plays a role in enhancing the bending resistance and stiffness. Moreover, the more stable microscopic structure may have contributed to a more uniform stress distribution during the bending tests (Bhat *et al.,* 2009).

In contrast, treatment P3 exhibited the lowest mechanical performance, with MOE and MOR values of 650.3 N/mm^2 and 6.13 N/mm^2, respectively. The dominance of sengon flour, which has a low D, high porosity, and high water uptake, likely weakened the fiber–matrix interfacial bonding, resulting in poor resistance to bending and deformation. The low D and high MC of this treatment likely also contributed to the reduced mechanical properties (Hadi *et al.,* 2022). As noted by Zhao *et al.* (2022), composites with higher moisture levels tend to exhibit reduced adhesion and mechanical

Table 3. Mechanical properties of WPC samples under different treatments

Treatments	MOE (N/mm^2)	MOR (N/mm^2)	Tensile strength (N/mm^2)	Impact strength (J/mm^2)	IBS (MPa)
P1	827.6^a ± 43.58	11.60^a ± 0.44	7.35^a ± 1.25	0.0071 ± 0.0003	1.52^a ± 0.27
P2	725.1^b ± 19.91	7.96^b ± 0.94	5.88^b ± 0.95	0.0069 ± 0.0005	1.38^b ± 0.34
P3	650.3^c ± 29.30	6.13^c ± 1.65	3.89^c ± 0.84	0.0066 ± 0.0005	1.22^c ± 0.44
P4	1,001.4^d ± 51.64	12.04^d ± 2.46	8.12^d ± 0.91	0.0084 ± 0.0004	1.03^d ± 0.47

$^{a-d}$ Values in the same column followed by different letters indicate significant differences ($p < 0.05$) based on the LSD post hoc test.
WPC: wood-plastic composites, MOE: modulus of elasticity, MOR: modulus of rupture, IBS: internal bond strength.

bond integrity.

Treatments P1 and P2 exhibited moderate MOE and MOR values, following the general trend that increasing ulin content leads to improved mechanical strength as ulin wood is denser, durable, and more compatible with polyester resins than sengon wood. Franke and Volkmer (2021) evaluated tropical hardwood fibers in thermoplastic composites and reported that the superior mechanical behavior of ulin also helps minimize deformation under load.

The σt values of WPC varied significantly among treatments (α = 5%), ranging from 3.89 N/mm^2 (P3) to 8.12 N/mm^2 (P4). Although SNI 8514:2015 does not explicitly specify a minimum requirement for this parameter, the values obtained indicate that the composites possess adequate tensile characteristics for nonstructural applications, such as decorative panels, furniture components, and interior cladding. Treatment P4 exhibited the highest st (8.12 N/mm^2). This suggests that the absence of chemical treatment does not necessarily compromise the tensile performance and may even help preserve the natural lignocellulosic integrity of the ulin fibers, which in turn help them resist tensile loads. Ayrilmis *et al.* (2011) found that the natural structure of hardwood, such as oak and teak, contributes significantly to the composite σt, particularly when the filler dispersion is uniform and not disrupted by harsh chemical reactions.

In contrast, P3 exhibited the lowest st (3.89 N/mm^2), which can be attributed to the lower D, higher MC, and porous fiber structure of sengon wood, all of which reduce the bonding strength between the filler and the matrix. Similar trends were reported by Zou *et al.* (2020), who observed that plant-based fibers with loosely packed morphologies result in weaker stress transfer and lower tensile resistance in polymer composites. Meanwhile, P1 and P2 displayed moderate tensile performance, with higher ulin content correlated with improved σt. This is primarily due to the higher D and stiffness of the ulin wood, which in turn forms more effective stress-transferring networks between the filler and the polyester matrix. Bafti and Habibolahzadeh (2013) also highlighted that the intrinsic stiffness of natural fibers is critical for supporting the st of polymer composites.

The IS values of the WPC samples differed significantly across treatments, ranging from 0.0066 (P3) to 0.0084 J/mm^2 (P4). Although SNI 8514:2015 does not specify a particular standard for IS, this test is essential for evaluating the ability of a material to absorb impact energy before failure, particularly for applications requiring resistance to sudden loading. Treatment P4 had the highest IS (0.0084 J/mm^2), indicating that the internal structure of the composite was sufficiently robust to resist impact energy despite the absence of alkali treatment. The preservation of natural lignin, which is not degraded by NaOH, likely contributed to the effective energy absorption during impact. Das *et al.* (2021) noted that fibers with dense and smooth natural structures could distribute the impact stress more evenly throughout the polymer matrix.

In contrast, P3 exhibits the lowest IS (0.0066 J/mm^2). This result aligns with the physical characteristics of sengon wood, which is lighter and more porous, resulting in weaker interfacial bonding and greater susceptibility to cracking or deformation under impact. Poor stress distribution across the interface may also reduce the localized bonding strength (Zou *et al.,* 2020). The P1 and P2 treatments exhibited intermediate values of 0.0071 and 0.0069 J/mm^2, respectively. While the presence of ulin enhanced the impact resistance, alkali treatment in these two groups may have slightly reduced the fiber flexibility, limiting their ability to absorb dynamic energy.

Lastly, the IBS of the WPC panels differed significantly across treatments (α = 5%), with the highest value recorded in P1 (1.52 MPa) and the lowest in P4 (1.03 MPa). Although SNI 8514:2015 does not explicitly specify a minimum IBS threshold, equivalent standards such as JIS A 5908:2003 suggest a minimum of 0.20–0.40 MPa for standard-grade particleboard, indicating that all treatments in this study meet the IBS requirement for light-duty applications.

Treatment P1 exhibited the highest IBS value. The high D and low MC of this treatment likely allowed for tighter contact between the wood particles and stronger interfacial adhesion with the polyester matrix. Increasing the proportion of hardwood with dense cell wall structures positively contributes to the internal bonding strength because it enables more effective compaction during fabrication (Franke and Volkmer, 2021).

By contrast, P4 had the lowest IBS value. Although this treatment showed high MOE and MOR, its low IBS may be attributed to weak bonding between the wood particles and the matrix owing to the absence of an alkali treatment. Without soaking in NaOH, wood particles retain hydrophobic extractives and surface contaminants that hinder resin penetration and mixing (Khalil *et al.*, 2012). Consequently, more interfacial voids were formed, reducing the cohesive strength of the composite.

The IBS values of treatments P2 and P3 were moderate and showed a decreasing trend with increasing sengon content. The porous, lightweight, and rough-textured nature of sengon flour may reduce compaction efficiency and resin distribution during molding, leading to weaker interlayer bonding. This finding aligns with that of Bhat *et al.* (2009), who reported that the physical characteristics of the filler materials significantly influence the interfacial bonding quality in thermoset resin-based composites.

Interestingly, treatment P4, which used untreated ulin wood flour, exhibited the highest values across all measured mechanical properties, including MOE, MOR, σt, and IS. This result appears counterintuitive, as alkali pretreatment is generally expected to enhance the fiber–matrix adhesion and, in turn, improve the composite strength. However, several studies have shown that excessive or suboptimal NaOH treatment can negatively affect fiber quality.

One possible explanation for this counterintuitive finding is that the alkali treatment might partially degrade the ulin fibers by removing hemicellulose and other structural components, leading to a weaker internal bonding capacity. High-concentration or prolonged alkali exposure can embrittle lignocellulosic fibers, reducing their reinforcement potential (Gassan and Bledzki, 1997). Additionally, polyester resins, which are highly reactive and rigid, may not interact optimally with overmodified fiber surfaces, leading to suboptimal stress transfer at the interface.

This finding suggests that alkali treatment, while beneficial for improving moisture resistance, must be carefully optimized to prevent fiber damage and maintain compatibility with the polymer matrix. The performance of P4 highlights the importance of balancing chemical modification with fiber integrity, particularly when using thermoset resins such as polyesters.

Visual inspection of the wood flour morphology under macrolens imaging (Fig. 1) revealed noticeable differences in particle color and texture, which reflected the composition and treatment conditions. Wood color is an essential indicator that can be used to assess wood quality, especially for decorative products. The color of wood can be improved by modifying wood (Dirna, 2024). Flours containing higher proportions of ulin tended to appear darker and coarser, whereas those dominated by sengon exhibited a lighter, more fibrous structure. The alkali-treated samples exhibited a relatively cleaner surface with fewer dark extractives, suggesting the effective removal of lignin and wax. These morphological differences are expected to influence the fiber–matrix interactions and, subsequently, the composite performance.

Although the mechanical properties of all the WPC treatments did not meet the minimum thresholds set by SNI 8514:2015 for structural panels, the composites still demonstrated moderate and consistent performance across the MOE, MOR, tensile, impact, and IBS metrics. When assessed against the performance benchmarks of ASTM D7031 and JIS A 5908 for general-purpose

Fig. 1. Morphological appearance of ulin-sengon wood flour mixtures under different blending ratios and alkali treatment conditions. (a) 75% ulin:25% sengon, (b) 50% ulin:50% sengon, (c) 25% ulin:75% sengon, (d) 50% ulin:50% sengon.

panels, these results indicate that the materials are suitable for non-structural applications such as interior wall paneling, ceiling boards, partition walls, and decorative furniture elements. This reinforces their potential use in lightweight constructions, where dimensional stability and durability outweigh the need for a high mechanical load-bearing capacity.

4. CONCLUSIONS

In this study, we demonstrated that the composition of ulin and sengon wood flours, along with the application of a 5% NaOH alkali pretreatment, significantly influenced the physical and mechanical properties of WPCs made with unsaturated polyester resin. Statistical analysis confirmed that treatment variations significantly impacted most characteristics of WPC, except D and IS. Among the four formulations included in the study, treatment P4 exhibited the best overall mechanical performance in terms of MOE, MOR, σt, and IS, whereas treatment P1 exhibited the highest IBS. These findings suggested that alkaline pretreatment does not always enhance mechanical performance and, in some cases, may compromise fiber integrity owing to overtreatment.

Although none of the WPC treatments satisfied the mechanical strength thresholds set by SNI 8514:2015 for structural use, they exhibited adequate dimensional stability and consistent mechanical properties. Evaluating their performance with the performance benchmarks of ASTM D7031 and JIS A 5908 revealed that the materials are suitable for nonstructural applications, such as interior wall cladding, ceiling panels, partitions, and furniture components. These findings highlight the potential of WPC using ulin and sengon as viable alternatives to lightweight, moisture-resistant, and non-load-bearing construction elements.

CONFLICT of INTEREST

No potential conflict of interest relevant to this article was reported.

ACKNOWLEDGMENT

The author would like to express sincere gratitude to the Dean of the Faculty of Forestry and Tropical Environment, Mulawarman University, Prof. Dr. Irawan Wijaya Kusuma, S. Hut., and M.P. for their valuable support and opportunity to carry out this research. Special appreciation is also extended to Vice Dean I for Academic Affairs and Prof. Dr. Harlinda Kuspradini, S. Hut., M.P., for the research funding assistance that made this study possible. Their support was instrumental in the successful completion of this research project.

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